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RESEARCH MEMORANDUM

ALTITUDE-TEST-CHAMBER INVESTIGATION OF PERFORMANCE OF A 28-INCH RAM-JET ENGINE

IV - EFFECT OF INLET-AIR TEMPERATURE, COMBUSTION-CHAMBER-INLET MACH NUMBER, AND FUEL VOLATILITY ON COMBUSTION PERFORMANCE

By Robert W. Kahn, Shigeo Nakanishi, and James L. Harp, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON
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RESEARCH MEMORANDUM

ALTITUDE-TEST-CHAMBER INVESTIGATION OF PERFORMANCE OF A 28-INCH RAM-JET ENGINE

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SUMMARY

As part of a direct-connect altitude-test-chamber investigation of the combustion performance of a 28-inch-diameter ram-jet engine conducted at the NACA Lewis laboratory, the effects of the following variables on combustion performance were determined:

1. Inlet-air temperature (150° to 350° F)

2. Combustion-chamber-inlet Mach number and pressure (values associated with 55- and 65-percent exhaust nozzles)

3. Fuel density and volatility (commercial grade normal heptane and high-speed Diesel fuel)

In general, increasing inlet-air temperature extended the operable range of fuel-air ratios and permitted operation at lower combustion-chamber pressures. Increasing the inlet-air temperature also increased the combustion efficiency at conditions of high fuel-air ratio and high combustion-chamber-outlet pressure. Raising the combustion-chamber-inlet Mach number and simultaneously lowering the combustion-chamber pressure by increasing the size of the exhaust-nozzle area resulted in increasing the minimum operational combustion-chamber-outlet pressure, lowering the combustion efficiency, and reducing the lean limit of combustion. The use of high-speed Diesel fuel decreased the combustion efficiency 20 to 30 percent below that obtained with heptane within a comparable range of fuel-air ratios.

INTRODUCTION

An investigation of the altitude performance of a 28-inch-diameter ram-jet engine has been conducted in a 10-foot-diameter altitude test chamber at the NACA Lewis laboratory. This engine is being developed by the Marquardt Aircraft Company for use in a Grumman Aircraft Engineering Corporation test vehicle as part of a Navy guided-missile project. The missile is to be ground-launched by a rocket booster and is to climb under its own power to a cruising altitude of 50,000 feet. A flight Mach number of 2.0 will be maintained throughout most of the climb and cruise conditions. 2157

Results of earlier phases of the investigation on this engine in the altitude test chamber are reported in references 1 to 3. In this earlier work, a wide range of combustion-chamber configurations was investigated and designs suitable for operation throughout the high-altitude part of the missile flight plan were determined. All runs were made at a simulated flight Mach number of 2.0 and at simulated altitudes from 35,000 to 55,000 feet. During these phases of the investigation the engine was equipped with an exhaust nozzle having a throat area equal to 55 percent of the combustion-chamber area.

The final phases of the program reported herein were conducted to investigate the effects of deviations from standard design and operating conditions. The deviations were in inlet-air temperature, exhaust-nozzle area, and fuel type. The inlet-air temperature was varied to simulate operation at off-design flight Mach numbers. The effect of a larger exhaust nozzle upon combustion performance was investigated because an exhaust nozzle larger than that previously used might be needed on the flight engine to meet the thrust requirements for acceleration following booster separation. High-speed Diesel fuel was used to determine the effect of fuel volatility on combustion performance because availability might necessitate the use of other than the design fuel, heptane.

The effect of these deviations was investigated on an engine equipped with a 65-percent exhaust nozzle and one of the best of the combustion-chamber configurations evaluated during the previous part of the test program. Data were obtained at inlet-air temperatures of 150°, 250°, and 350° F with normal heptane fuel and at 250° F with Diesel fuel. Comparisons are made to show the effect of inlet-air temperature on the limits of combustion and combustion efficiency. The effects of combustion-chamber-inlet Mach number and pressure on combustion limits, combustion efficiency, and combustion-chamber pressure ratio are shown by a comparison of data obtained for operation of the engine with the 65-percent exhaust nozzle used in the investigation reported herein with the data reported in the investigation of

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reference 3 in which a 55-percent nozzle was used. Comparisons of the combustion efficiencies obtainable with normal heptane and Diesel fuel are also presented.

APPARATUS

Description of Engine

A schematic drawing of the engine is shown in figure 1(a). The internal design of the test engine is similar to that of the flight engine. For the altitude-test-chamber investigation, a bellmouth convergent-divergent inlet nozzle (surrounding the flight engine diffuser cone) accelerated the inlet air from stagnation conditions in the test chamber to a Mach number of about 1.6 at a position corresponding to the lip of the flight engine at station 31 (31 in. from nozzle inlet). The Mach number of 1.6 at the lip position corresponds to the lip Mach number of the flight engine at a flight Mach number of 2.0. Four inner-body support longerons spaced 90° apart and extending from station 35 to the aft end of the inner body provided four separate flow channels for the air entering the combustion chamber. The flame holder and center pilot burner were mounted at the aft end of the inner body. The combustion chamber, which was the same chamber used in the investigation of reference 3, had an effective length of approximately 57 inches. A convergent-divergent exhaust nozzle followed the combustion chamber and had a throat area which was 65 percent of the combustion-chamber area.

A detailed description of the fuel system, flame holder, and pilot-burner assembly used is given in reference 3 (configuration 2, reference 3). From preliminary runs it was found that the flame holder in configuration 2 of reference 3 gave better operating limits with the 65-percent exhaust nozzle although the flame holder of configuration 1 was the best when used in conjunction with the 55-percent nozzle.

Fuel was injected at station 208 (fig. 1(b)) in each of the four quadrants (formed by the inner-body support longerons) through four double-manifold circular-arc segments. The manifold segments were supported on hollow struts, which were channeled to permit individual control of flow to either the inner or outer manifold segment. Spring-loaded fuel-injection nozzles, similar to those described in reference 1, discharged upstream. The same nozzles were used for both heptane and Diesel fuel although a less-favorable spray pattern and poorer atomization might be expected from the more viscous Diesel fuel.

The flame holder (fig. 2) had a projected blocked area of 45 percent of the combustion-chamber area and the width of the two annular gutters was 2 inches. Flare cases were mounted in three locations on the flame holder. Although flares were not used in starting the engine, one flare case that was equipped with a fuel nozzle, a spark plug, and air admission holes was used as an alternate igniter for the test engine when the pilot-burner ignition failed to operate. 2157

The can-type pilot burner was mounted on the blunt end of the diffuser inner body. An exploded view of the pilot burner and flame holder assembly is shown in figure 3. The pilot burner was made of a 6-inch-diameter swirl plate mounted on 1/2-inch spacers on the blunt end of the inner body. A tapered skirt, 4.4 inches long and 7.8 inches in diameter at the downstream end, was attached to the downstream face of the swirl plate. The pilot burner provided an additional 7.7-percent blocked area.

Installation in Altitude Test Chamber

A schematic drawing of the engine mounted in the altitude test chamber is shown in figure 4. A front baffle fitted with a diaphragm seal provided an air tight separation between the inlet section, which was at ram pressure, and the test section, which was at exhaust pressure. A rear baffle surrounding the engine near the exhaust nozzle prevented the hot exhaust gases from recirculating around the engine. Other details of the installation are given in reference 1.

The engine inlet air was preheated to the required temperature by mixing the inlet air with products of combustion from a can-type combustor in the inlet-air line. Heptane fuel was used for the preheater. In order to obtain inlet temperatures varying from 150° to 350° F, a range of preheater fuel-air ratios from 0.001 to 0.004 was required. The effects of contamination of the inlet air by the products of combustion at these fuel-air ratios were not considered in evaluating the combustion-chamber performance. The fuel-air ratio of the engine, however, was evaluated on the basis of unburned air entering the engine combustion chamber and thus excluded the preheater fuel.

Instrumentation

The fuel flow was measured with a calibrated adjustable orifice meter. Air flow was determined from a calibration of the choked bellmouth-inlet nozzle of the engine. This calibration was used instead of direct measurements of air flow obtained from the sharp-edge orifice in the inlet-air supply line in order to reduce data scatter brought about by pressure fluctuations in the air supply line.

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The engine-inlet total temperature and pressure were measured by thermocouple and pressure rakes at the bellmouth inlet. The locations of temperature and static- and total-pressure measurements within the engine are shown in figure 1(a). Total- and static-pressure surveys across the annular diffuser were made about 13 inches upstream of the flame holder in two of the four quadrants. Static pressures were measured for reference purposes along the wall of the inner body and along the wall of the water-jacketed combustion chamber. A water-cooled rake extending across the diameter was used to measure the total pressure at the combustion-chamber outlet. Static pressure in the exhaust-nozzle throat was measured by wall static tubes and by water-cooled trailing static tubes mounted on the total-pressure rake in the combustion-chamber outlet and extending downstream past the nozzle throat. The blocked area created by these tubes was 0.28 percent of the nozzle-throat area and was considered negligible.

PROCEDURE

The general procedure followed in starting the engine was to set the bellmouth-inlet total pressure at approximately 34 inches of mercury absolute and the engine-outlet static pressure at approximately 28 inches of mercury absolute. With the inlet-air temperature established at the desired condition, the pilot burner was ignited. After stabilized burning was established in the pilot burner (as observed through a periscope), the main fuel flow was started. When burning in the combustion chamber was established, the exhaust pressure was reduced to a value lower than that required to choke the engine exhaust nozzle; the nozzle remained choked for all runs. The inlet-air total pressure and the total temperature were then adjusted to provide the flow conditions described in the following table:

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Inlet-air total temperature T_0 (°F)	Air flow (lb/sec)	Inlet-air total pressure P_0 (lb/sq ft abs.)	Simulated altitude (ft)	Simulated flight Mach number M_0
150	44	2820	33,500	1.62
	35	2215	38,100	1.65
	27	1730	43,300	1.65
250	44	3040	40,000	2.00
	35	2400	45,000	2.00
	27	1870	50,000	2.00
350	35	2560	49,700	2.30
	27	2010	54,800	2.30

The bellmouth-inlet pressures used for the 250° F inlet-temperature conditions gave air flows equal to those expected for supercritical operation of the flight ram-jet diffuser at altitudes of 40,000, 45,000, and 50,000 feet, thus simulating 2.0 Mach number conditions at these altitudes. The bellmouth-inlet total pressures for inlet temperatures of 150° and 350° F were set to give sets of data at air flows equal to those for the 250° F inlet-temperature conditions and resulted in simulated combustion-chamber operation at the flight Mach numbers and altitudes shown in the preceding table. The Mach number of 1.6 at the lip station corresponded only to that for a flight Mach number of 2.0. All regions of subsonic flow in the engine, however, have been assumed to simulate conditions in flight at the Mach numbers listed in the previous table. The runs with Diesel fuel were made at an inlet temperature of 250° F at simulated altitudes of 45,000 and 50,000 feet.

With the inlet pressure and temperature set, the fuel flow was varied to give small changes in fuel-air ratio and data were taken at stabilized burning conditions. Variation in the fuel-air ratio was continued until lean blow-out or rich blow-out was reached. Operation in the rich region was usually curtailed if rich blow-out was not reached between fuel-air ratios of 0.07 to 0.08.

Blow-out was detected by observation of the flame in the periscope, by observation of the action of photoelectric flame-sensing element attached to the combustion chamber, and by the change in the sound level. The fuel-air ratio and the combustion-chamber-outlet pressure defining blow-out were determined from observation of the fuel flow, air flow, and pressure values at the instant before blow-out.

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The fuels used were commercial grade normal heptane and high-speed Diesel fuel (U. S. Army Specification 2-102C, Amendment-3). The properties of these fuels were as follows:

Property	Normal heptane, commercial grade	High-speed Diesel fuel (U.S. Army Specification 2-102C, Amendment-3)
Reid vapor pressure, lb/sq in.	1.8	0
Specific gravity at 60°/60° F	0.725	0.833
Viscosity at 100° F, centistokes	0.5	2.8 to 3.1
Hydrogen-carbon ratio	0.179	0.158
Net heat value, Btu/lb	18,900	18,570
Distillation		
Initial boiling point, °F	203	360
Fifty-percent distillation point, °F	206	509
Final boiling point, °F	209	655
Residue, percent	0	3.5

Two methods of fuel injection were used and they are defined as follows: (1) uniform injection: injection at equal fuel pressures through all nozzles in both inner and outer manifolds (see fig. 1(b)), and (2) annular injection: injection only through the nozzles in the inner fuel manifold. Annular injection was used to extend the fuel-air ratio operating range to limits which were leaner than those obtainable with uniform injection.

Pilot fuel was obtained from a high-pressure source and was controlled independently of the fuel-manifold pressures (reference 3). The contribution of pilot fuel to the total fuel flow varied from 14.8 percent at a minimum total flow of 2456 pounds per hour to 3.0 percent at maximum total flow of 12,184 pounds per hour.

The symbols and the location of stations used throughout the report are defined in the appendix. Combustion efficiencies were calculated by the methods outlined in reference 2.

RESULTS

Effect of Combustion-Chamber Variables

The combustion-chamber performance data with inlet-air temperatures of 150°, 250°, and 350° F and with commercial grade normal heptane as the fuel are presented in figures 5 to 7. Performance parameters presented are the same as those presented in references 1 to 3 and, in general, follow similar trends. In these runs, the combustion-chamber-inlet Mach number data scattered to the extent that it was impossible to fair an accurate curve through the points. Consequently, theoretical curves computed from the calculated combustion-chamber-outlet temperature are shown superimposed on the data points in figures 5(d), 6(d), and 7(d). The effects of inlet-air temperature and combustion-chamber-inlet Mach number and pressure are discussed in subsequent paragraphs using cross plots from the curves presented in figures 5 to 7.

Effect of inlet-air temperature. - The effect of inlet-air temperature on limits of combustion with annular injection and with uniform injection is shown in figures 8(a) and 8(b), respectively. With annular injection, the limits of combustion extended to leaner fuel-air ratios and lower combustion-chamber-outlet pressures as inlet-air temperature increased. At a fuel-air ratio of 0.025, the minimum pressure for stable combustion decreased from about 1100 to 700 pounds per square foot as inlet-air temperature was increased from 150° to 350° F.

The limits of combustion with uniform injection followed the same general trends with inlet-air temperature. At a fuel-air ratio of 0.035, the minimum pressures for stable combustion decreased from 1170 to 680 pounds per square foot as inlet-air temperature increased from 150° to 350° F. The effect of inlet-air temperature at a fuel-air ratio of 0.055 was small and some reversal of trend occurred. As fuel-air ratio increased beyond 0.055, the effect of inlet temperature became more pronounced until at 0.07, the minimum stable combustion pressure decreased from 1550 to 800 pounds per square foot as inlet-air temperature increased from 150° to 350° F. The rich limit of combustion with an inlet-air temperature of 350° F was not determined for uniform injection because satisfactory operation was obtainable up to a fuel-air ratio of 0.07, the practical limit of operation.

The effect of inlet-air temperature on the combustion efficiency for uniform injection is shown in figure 9. The combustion efficiency increased with increasing inlet-air temperature. At a combustion-chamber-outlet pressure of 1400 pounds per square foot and a fuel-air ratio of 0.065, the combustion efficiency increased 0.20 as the inlet temperature increased from 150° to 350° F. At a combustion-chamber-outlet pressure of 1000 pounds per square foot and a fuel-air ratio of 0.040, the combustion efficiency increased 0.08 for the same increase in inlet-air temperature.

Effect of combustion-chamber-inlet Mach number and pressure. - The change in combustion-chamber-inlet Mach number and combustion-chamber-outlet pressure produced by a change in the exhaust-nozzle size is shown in figures 10(a) and 10(b), respectively. The curves of combustion-chamber variables and performance obtained with the 55-percent nozzle were obtained from reference 3. Performance at an altitude of 45,000 feet was compared because comparable sets of data at the design altitude of 50,000 feet were unavailable. At a simulated altitude of 45,000 feet, the combustion-chamber-inlet Mach number increased as much as 30 percent and the combustion-chamber-outlet pressure decreased from 20 to 28 percent for a change in exhaust-nozzle area from 55 to 65 percent. These effects are results of requirements for continuity of mass flow. The effect of these changes in operating conditions on combustion efficiency is shown in figure 10(c). For the range of fuel-air ratios between 0.047 and 0.077, the engine with the 55-percent exhaust nozzle had higher combustion efficiency for uniform injection. Below a fuel-air ratio of 0.03 with annular injection, the combustion efficiencies were about the same for both exhaust nozzles.

As shown in figure 11(a), the higher combustion-chamber-inlet Mach numbers associated with the use of the 65-percent nozzle shifted the envelope of combustion limits to a higher minimum pressure level and to lower fuel-air ratios. At a given pressure level, wider operating range (both lean and rich limits) would be expected with the 55-percent nozzle because the combustion-chamber-inlet velocity at a given fuel-air ratio and combustion efficiency would be lower. The improvement of the lean operation limits with the 65-percent nozzle may, however, be attributed to the effect of combustion-chamber-inlet velocity on fuel distribution, local rich zones being maintained more favorably in the vicinity of the flame holder by the higher gas velocities associated with the 65-percent nozzle.

As shown in figure 11(b), a higher combustion-chamber pressure ratio was obtained for the 55-percent exhaust nozzle than for the 65-percent nozzle for both annular and uniform injection. This higher pressure ratio is the result of lower combustion-chamber-inlet Mach numbers which were discussed previously.

Effect of Fuel Properties

The combustion-chamber performance with Diesel fuel at an inlet-air temperature of 250° F is shown in figure 12. The parameters shown in this figure follow trends similar to those for normal heptane with the exception of the combustion efficiency.

As previously stated, a theoretical curve was superimposed on the data for the combustion-chamber-inlet Mach number as shown in figure 12(d). A comparison of combustion efficiencies at an altitude of 45,000 feet using normal heptane and Diesel fuel at an inlet-air temperature of 250° F is shown in figure 13. For the range of fuel-air ratios 2157 investigated, the combustion efficiency with Diesel fuel was about 40 percent, which is from 20 to 30 percentage points lower than that obtained with normal heptane. While the combustion efficiency with Diesel fuel may be expected to increase with increasing fuel-air ratios, it is doubtful if it would become as high as that obtained with heptane fuel.

Because the viscosity of Diesel fuel was about 3.0 centistokes as compared to 0.5 for heptane, a higher injection pressure for Diesel fuel would be required to obtain a comparable degree of atomization for both fuels. When the same spray nozzles were used for Diesel fuel and heptane, approximately the same injection pressures for comparable fuel flows were required in both cases, which probably resulted in an inferior atomization of the Diesel fuel entering the combustion chamber. In addition, the 50-percent distillation point of the Diesel fuel used was 303° F higher than that for heptane, which would result in a lower rate of vaporization of the Diesel fuel. The poor quality of atomization, the low rate of evaporation, and the greater ignition-lag characteristics of Diesel fuel contributed toward the low combustion efficiency obtained.

SUMMARY OF RESULTS

A direct-connect altitude-test-chamber investigation conducted on a 28-inch-diameter ram-jet engine to determine the effect on combustion and operational performance of (1) inlet-air temperature, (2) combustion-chamber-inlet Mach number and pressure, and (3) a fuel of higher density and lower volatility than heptane gave the following results:

1. Increasing inlet-air temperature resulted in a wider fuel-air ratio operating range and lower pressures at which stable combustion could be maintained.

2. At a combustion-chamber-outlet pressure of 1400 pounds per square foot and a fuel-air ratio of 0.065, the combustion efficiency increased 0.20 for an increase in inlet-air temperature from 150° to 350° F. At a combustion-chamber-outlet pressure of 1000 pounds per square foot and a fuel-air ratio of 0.040, the combustion efficiency increased 0.08 for the same increase in inlet-air temperature.

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3. At a given simulated altitude, the higher combustion-chamber-inlet Mach numbers and lower combustion-chamber-outlet pressures obtained with the 65-percent nozzle resulted in a lower combustion efficiency for all fuel-air ratios except for the lean annular injection range.

4. Over the range of fuel-air ratios investigated (0.039 to 0.055) and at an inlet temperature of 250° F, the combustion efficiency for Diesel fuel was from 20 to 30 percent lower than for heptane.

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APPENDIX - SYMBOLS

The following symbols are used throughout this report:

A area, sq ft

M Mach number

P total pressure, lb/sq ft absolute

p static pressure, lb/sq ft absolute

T total temperature, $^{\circ}$F

W weight flow, lb/sec

η combustion efficiency

Subscripts:

0 conditions at engine inlet (station 0)

2 conditions at combustion-chamber inlet (station 228)

2' conditions at station 2 adjusted to combustion-chamber area

4 conditions at combustion-chamber outlet (station 292)

5 conditions at exhaust-nozzle throat (station 306)

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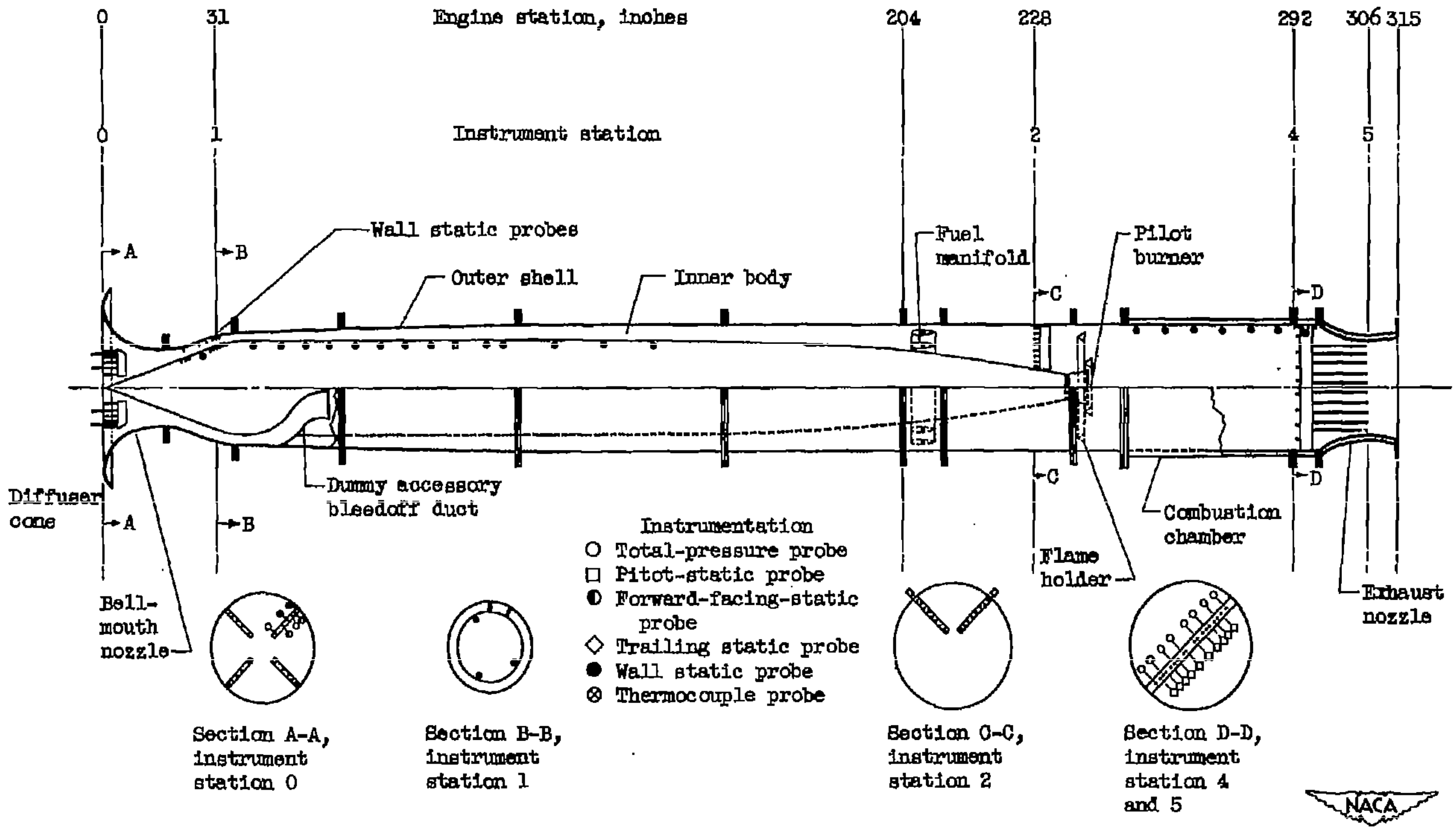
1. Jones, W. L., Shillito, T. B., and Henzel, J. G., Jr.: Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. I - Combustion and Operational Performance of Four Combustion-Chamber Configurations. NACA RM E50F16, 1950.

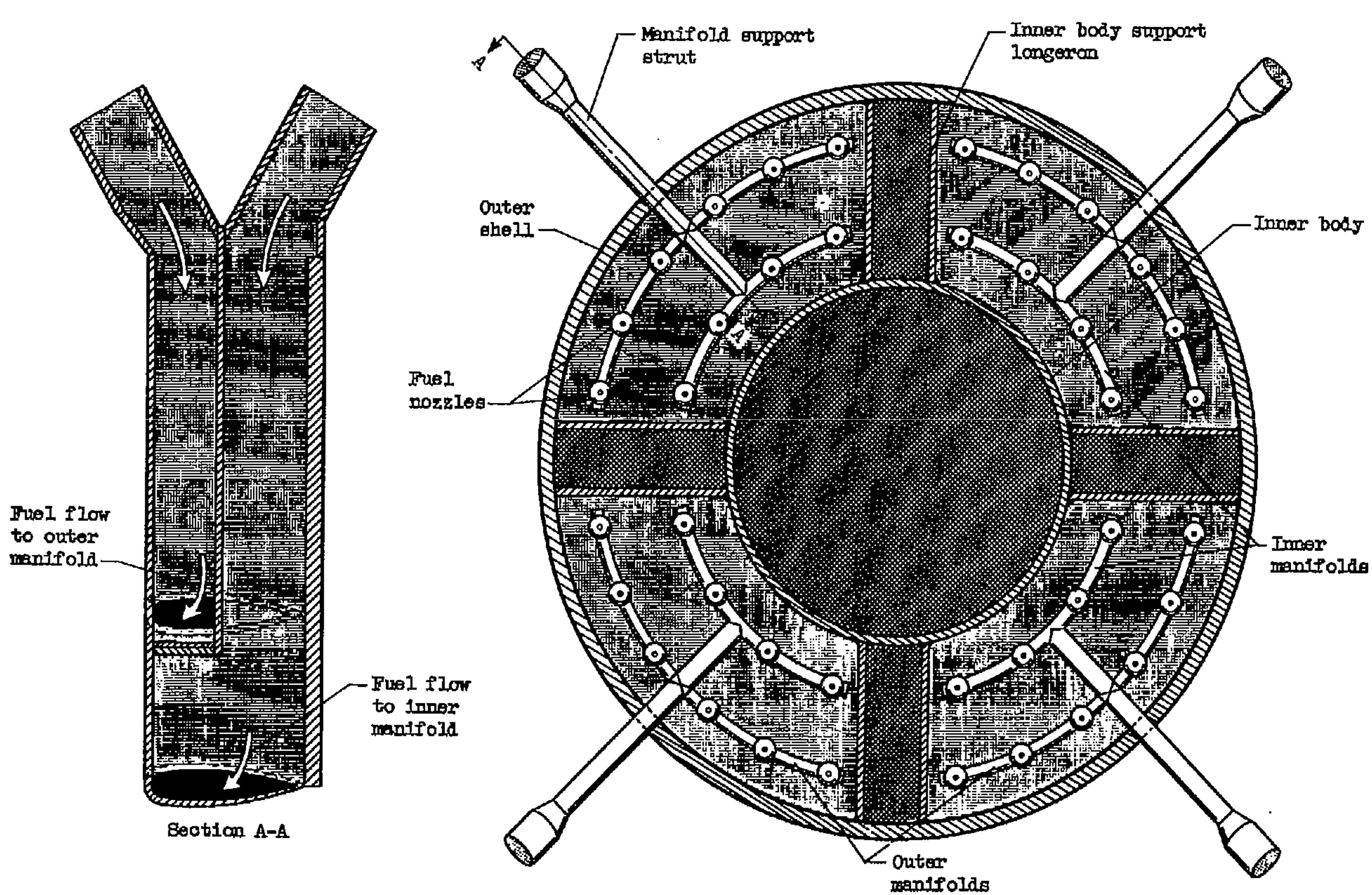
2. Shillito, T. B., Jones, W. L., and Kahn, R. W.: Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. II - Effects of Gutter Width and Blocked Area on Operating Range and Combustion Efficiency. NACA RM E50H21, 1950.

3. Shillito, Thomas B., Younger, George G., and Henzel, James G., Jr.: Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. III - Combustion and Operational Performance of Three Flame Holders with a Center Pilot Burner. NACA RM E50J20, 1950.



(a) Instrumentation and station locations.

Figure 1. - Schematic diagram of 28-inch ram-jet engine.



(b) Fuel manifolds (station 208).

Figure 1. - Concluded. Schematic diagram of 28-inch ram-jet engine.

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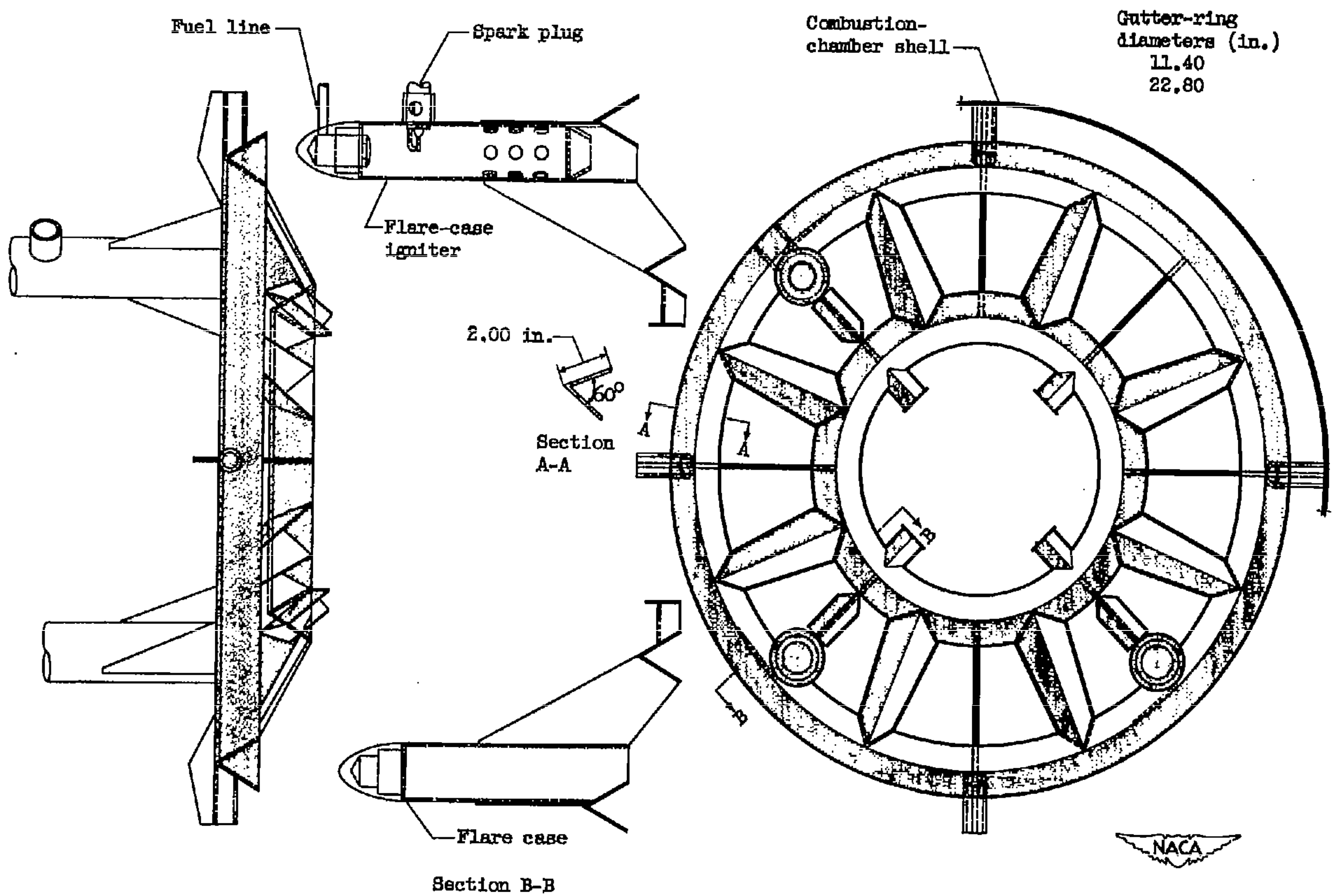

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Figure 2. - Flame-holder details. Gutter width, 2.0 inches; blocked area, 45.0 percent.

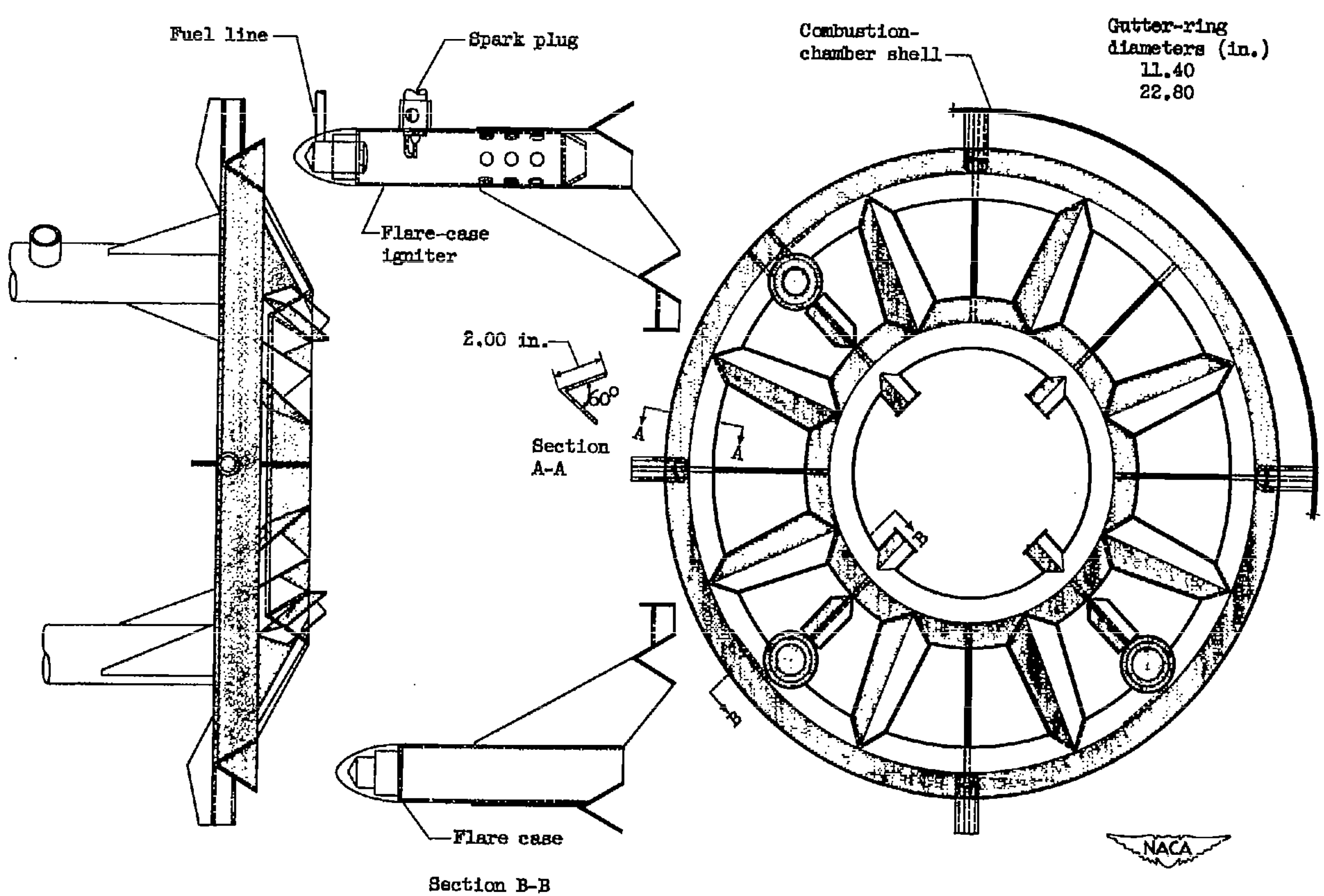

Figure 2. - Flame-holder details. Gutter width, 2.0 inches; blocked area, 45.0 percent.

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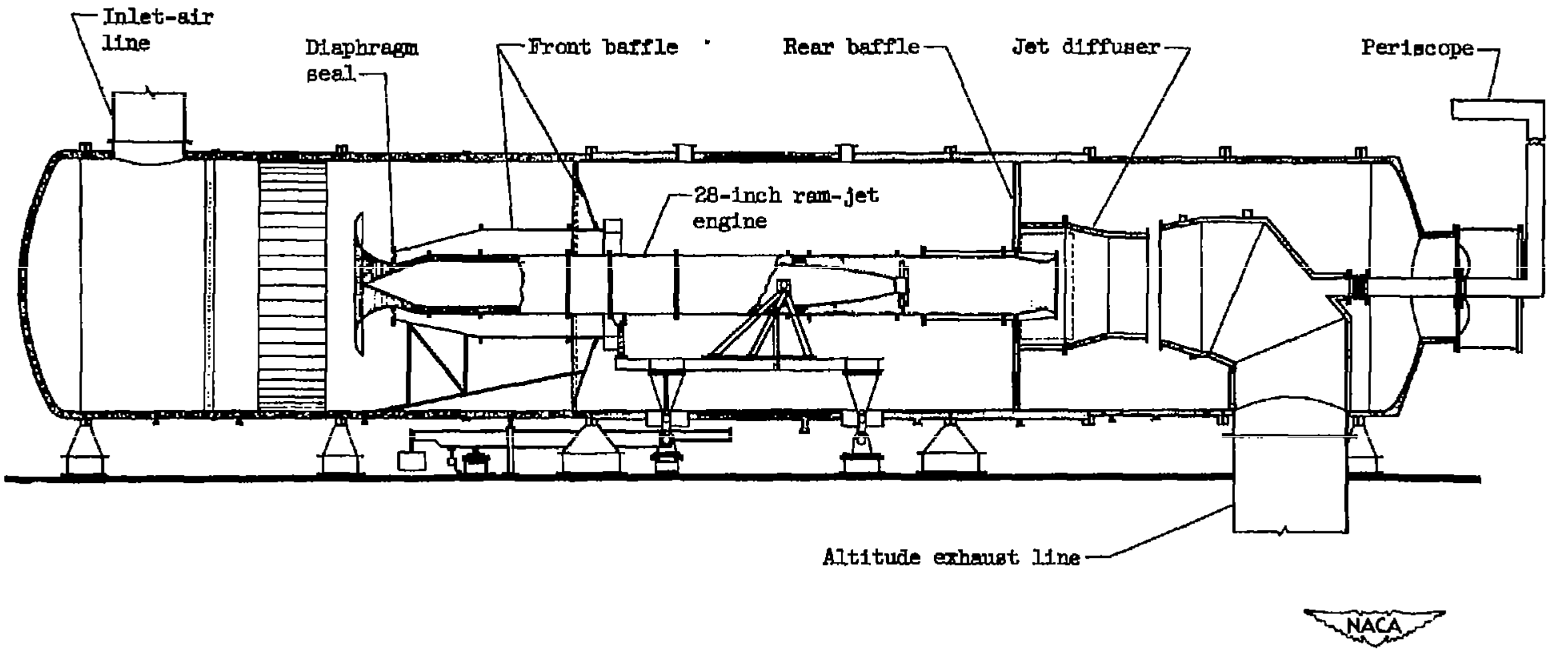

Figure 4. - Schematic diagram of 28-inch-ram-jet engine installation in 10-foot altitude chamber.

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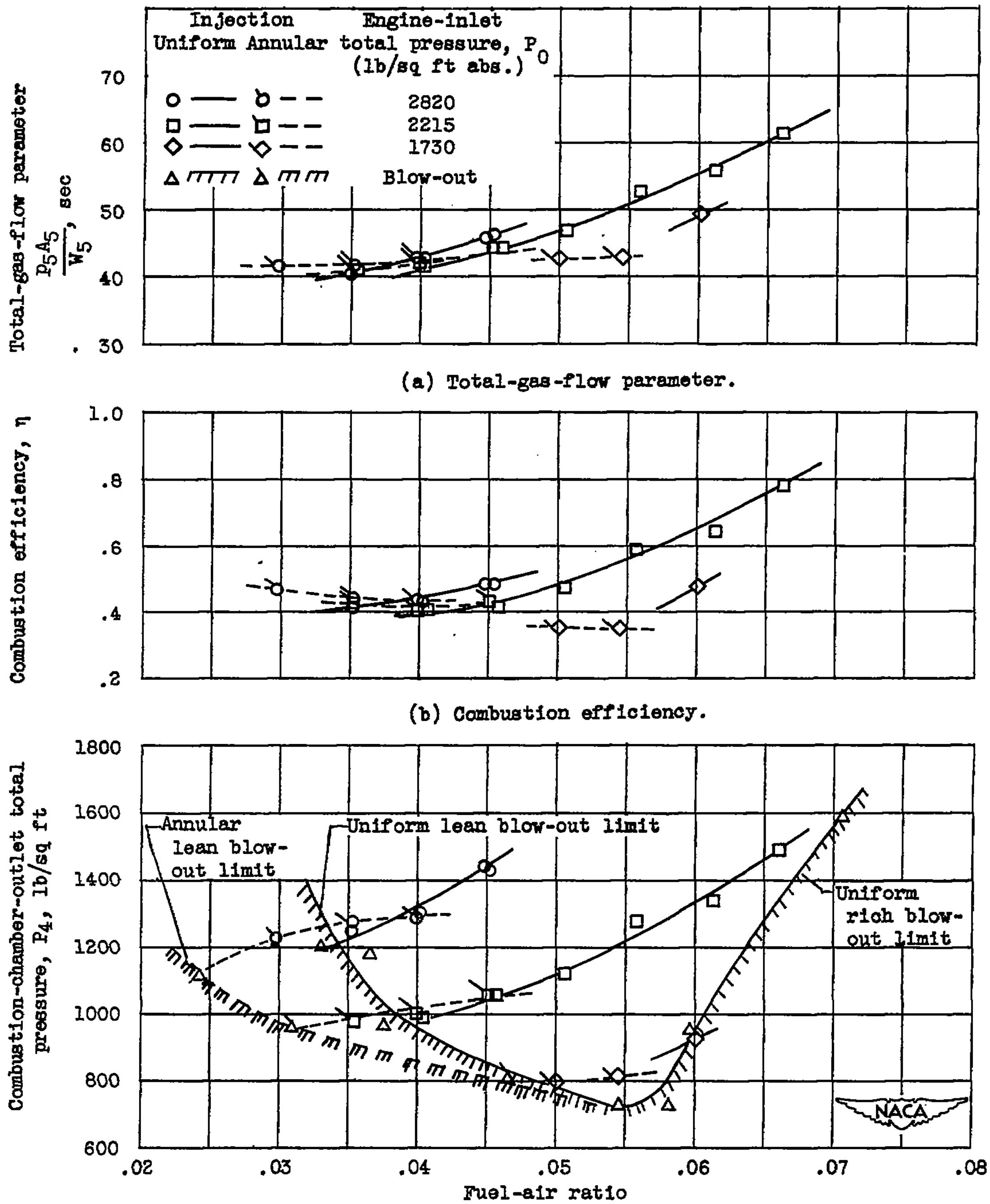

(a) Total-gas-flow parameter.

(b) Combustion efficiency.

(c) Combustion-chamber-outlet total pressure.

Figure 5. - Combustion results for 150° F inlet air. Fuel, normal heptane.

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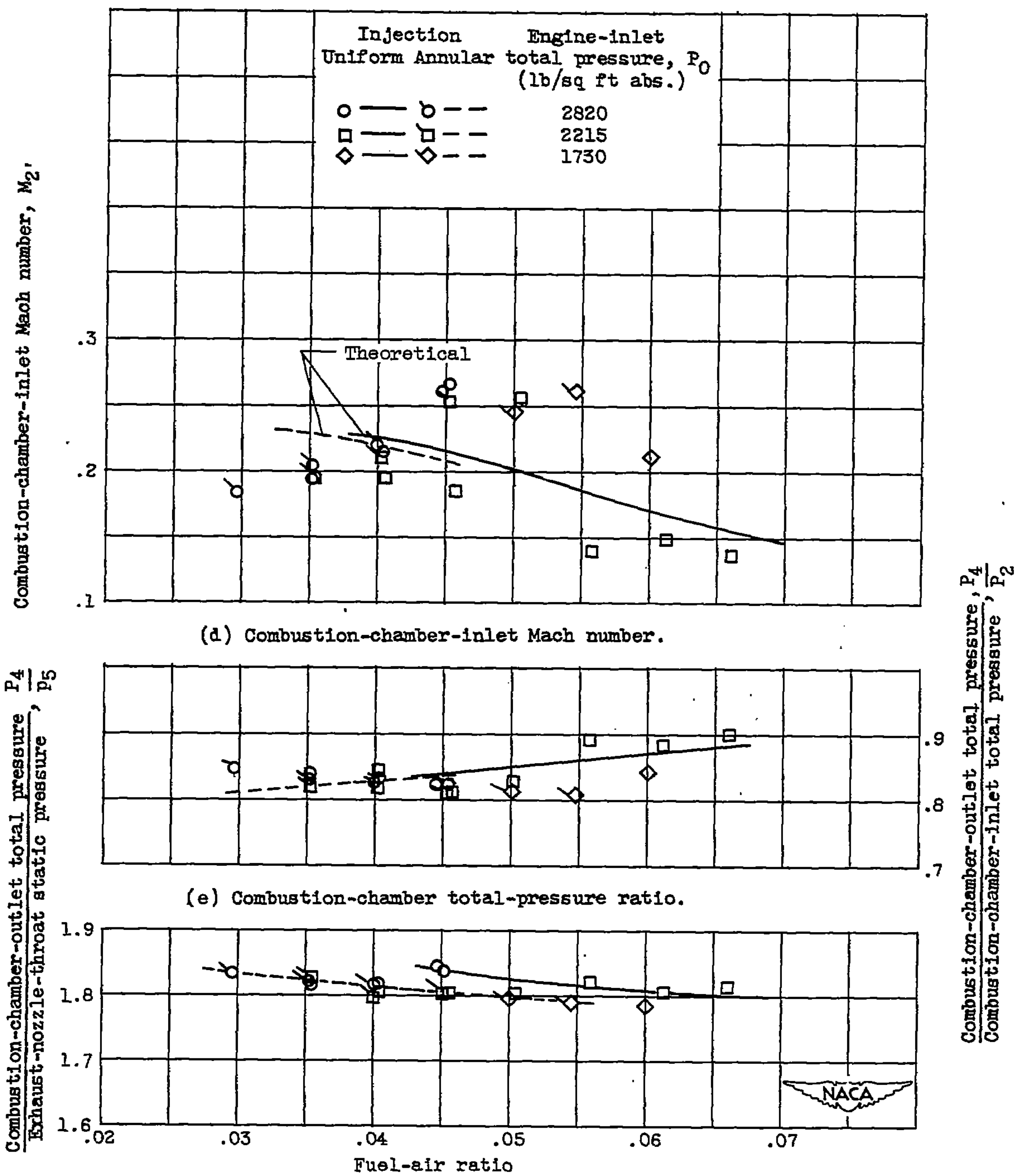
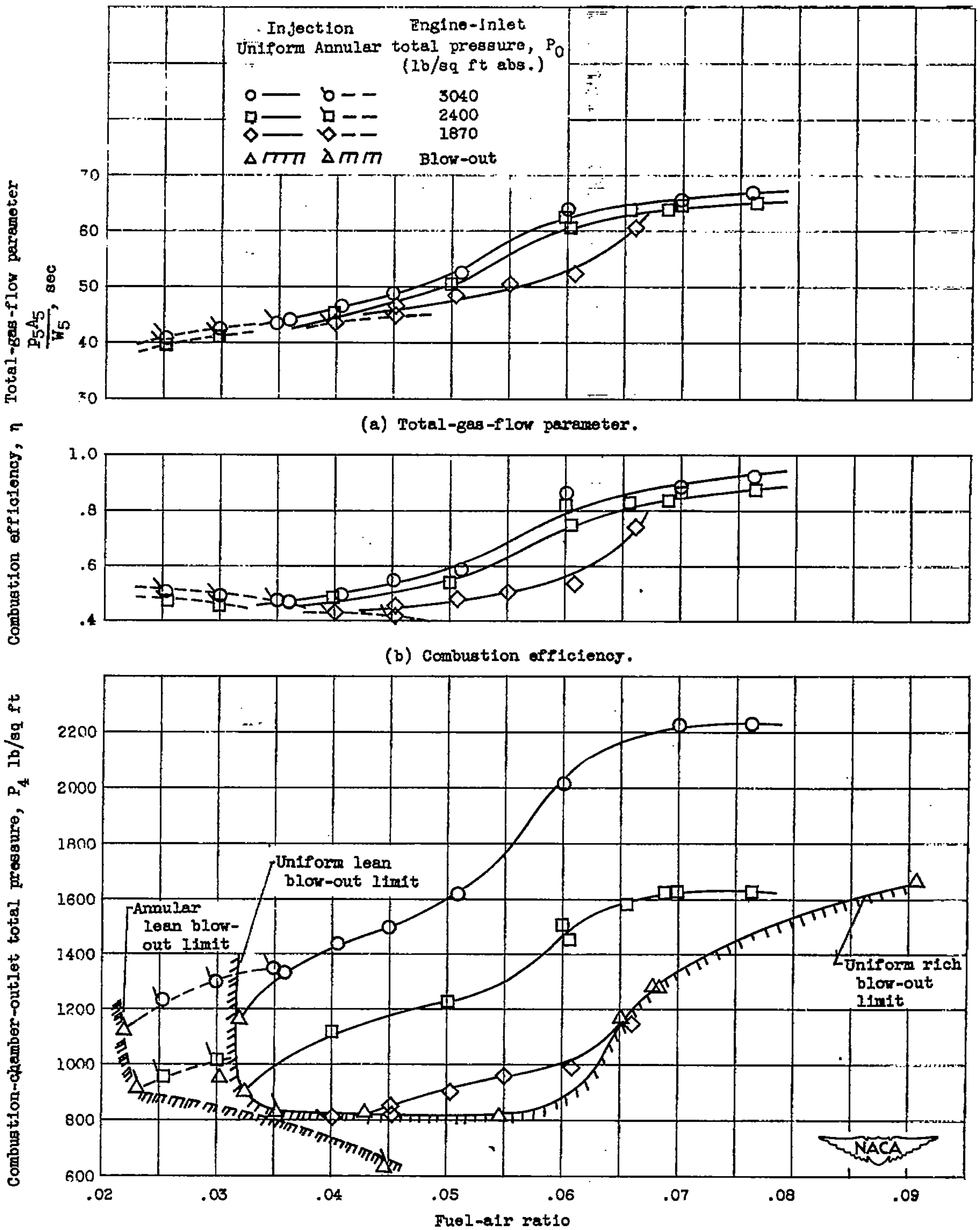


(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Combustion-chamber-outlet total-pressure and exhaust-nozzle-throat static-pressure ratio.

Figure 5. - Concluded. Combustion results for 150° F inlet air. Fuel, normal heptane.



(c) Combustion-chamber-outlet total pressure.

Figure 6. - Combustion results for 250° F inlet air. Fuel, normal heptane.

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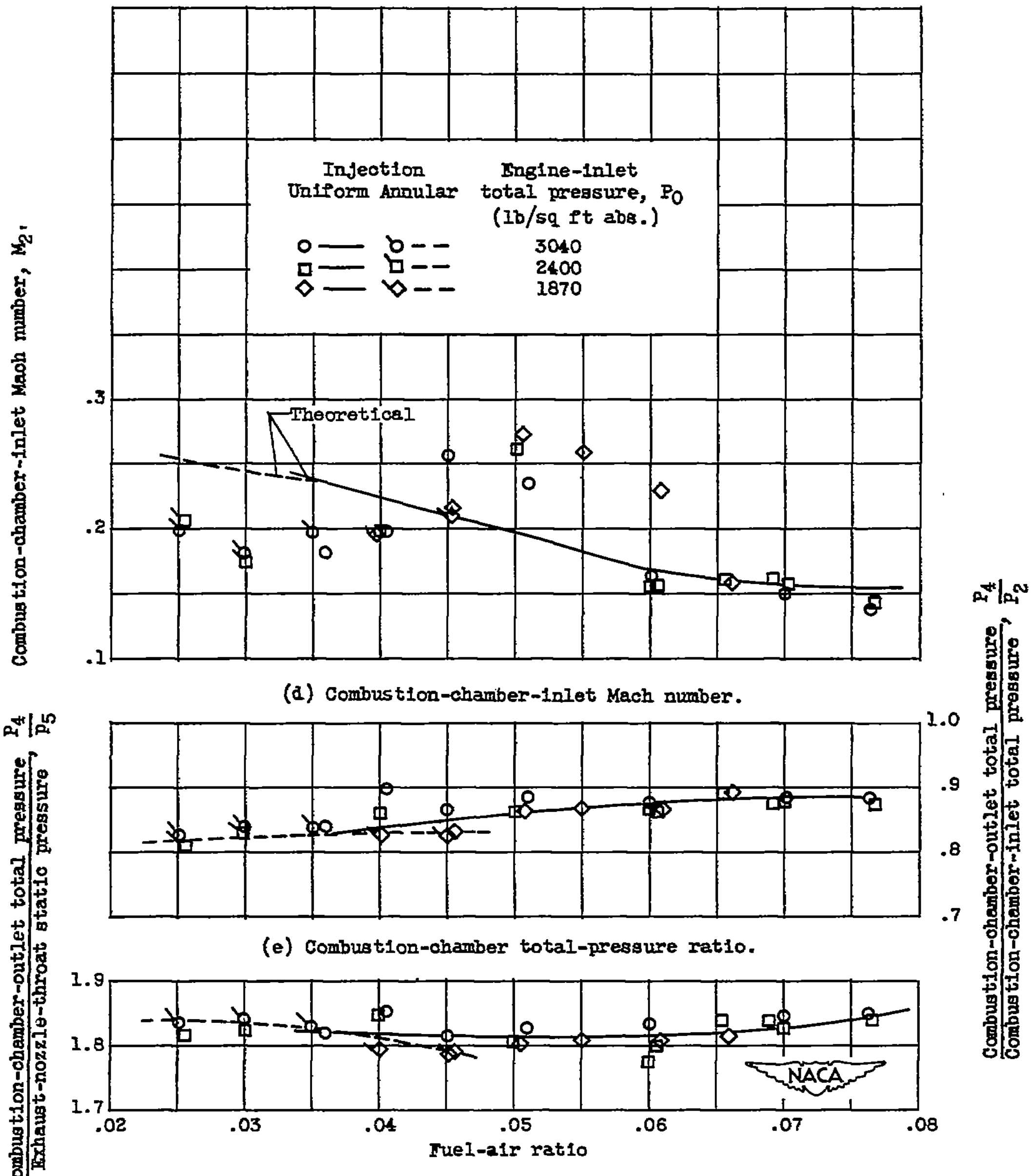

(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Combustion-chamber-outlet total-pressure and exhaust-nozzle-throat static-pressure ratio.

Figure 6. - Concluded. Combustion results for 250° F inlet air. Fuel, normal heptane.

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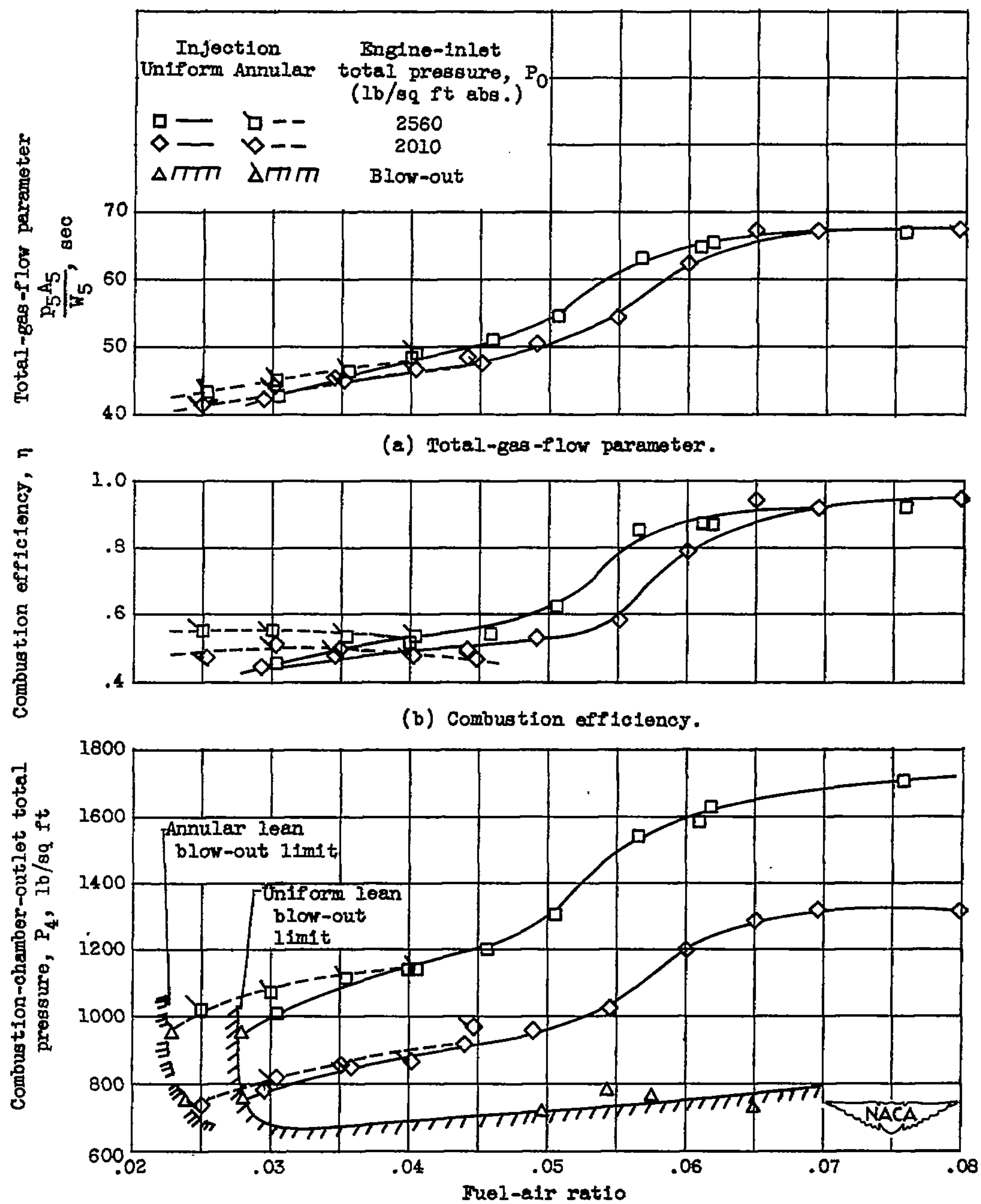

(a) Total-gas-flow parameter.

(b) Combustion efficiency.

(c) Combustion-chamber-outlet total pressure.

Figure 7. - Combustion results for 350° F inlet air. Fuel, normal heptane.

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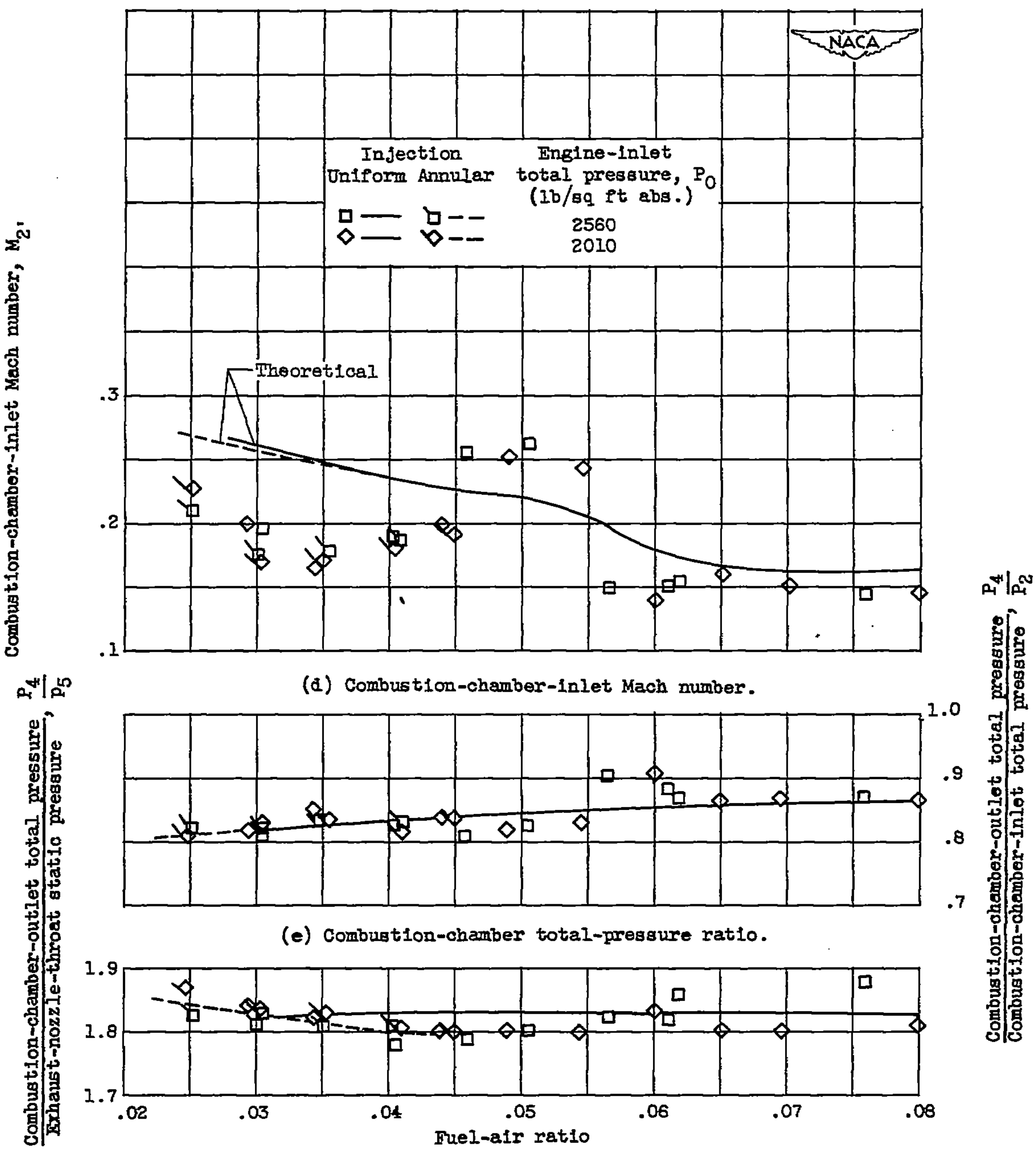

(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Combustion-chamber-outlet total-pressure and exhaust-nozzle-throat static-pressure ratio.

Figure 7. - Concluded. Combustion results for 350° F inlet air. Fuel, normal heptane.

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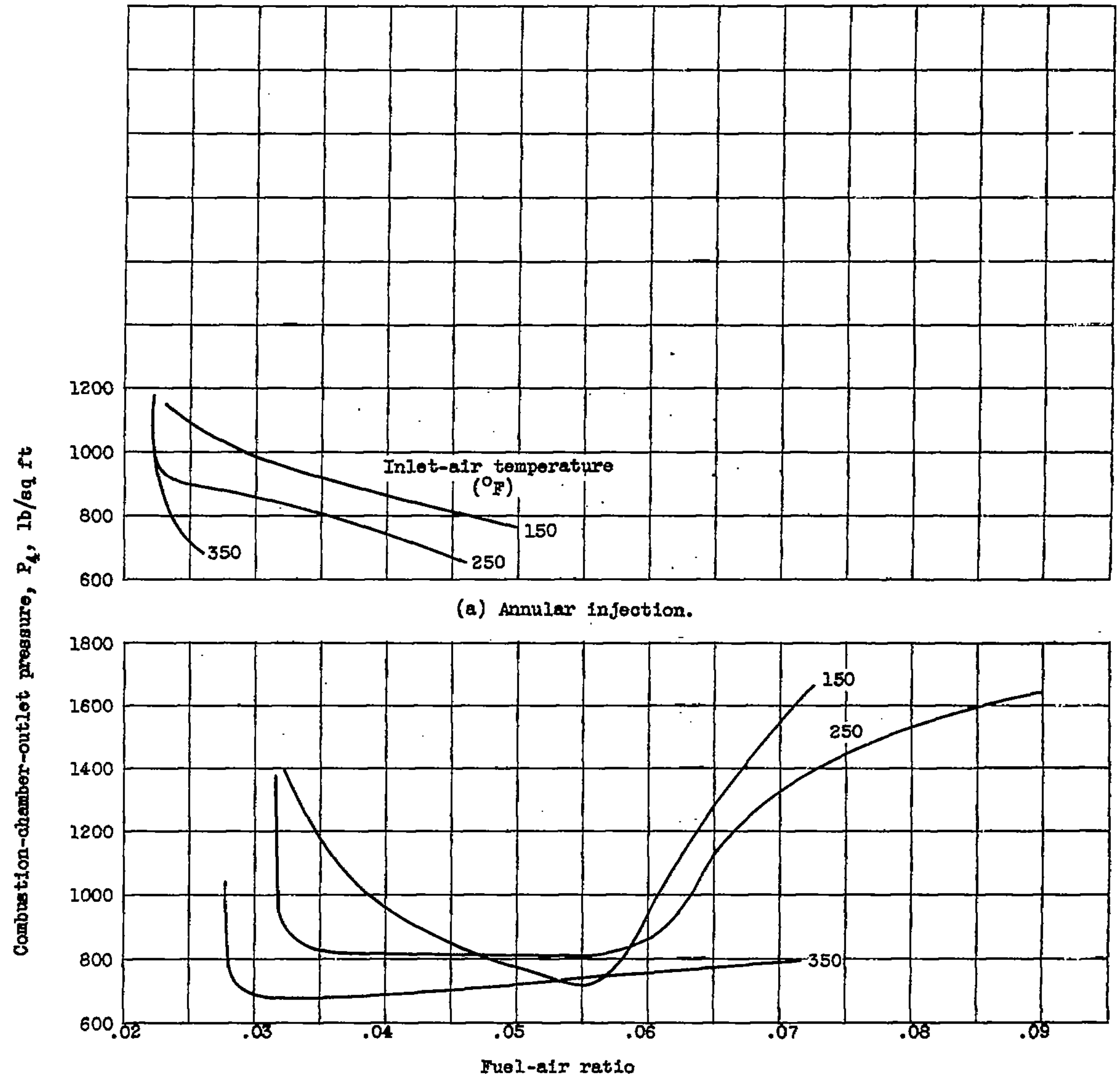


(b) Uniform injection.

Figure 8. - Effect of inlet-air temperature on combustion limits with 65-percent exhaust nozzle.

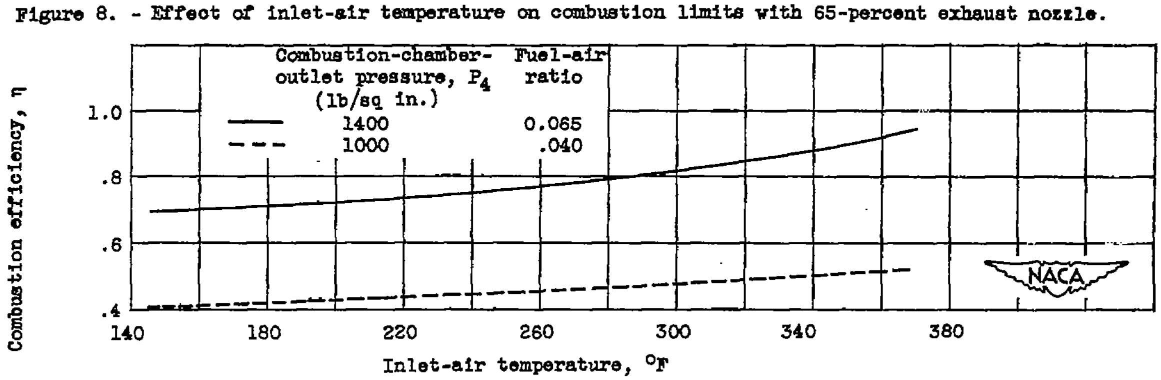
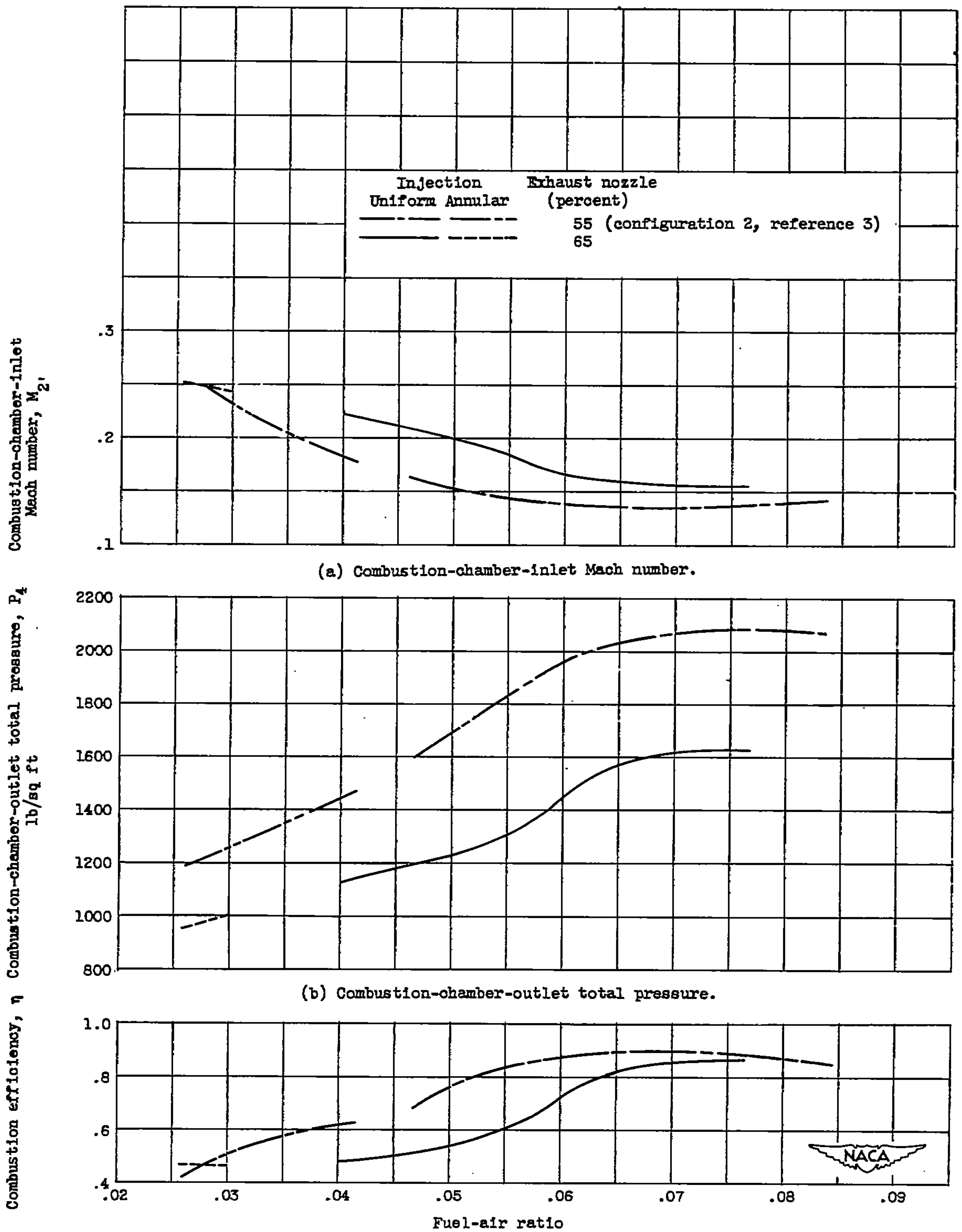


Figure 9. - Effect of inlet-air temperature on combustion efficiency with 65-percent exhaust nozzle and uniform injection. Fuel, normal heptane.

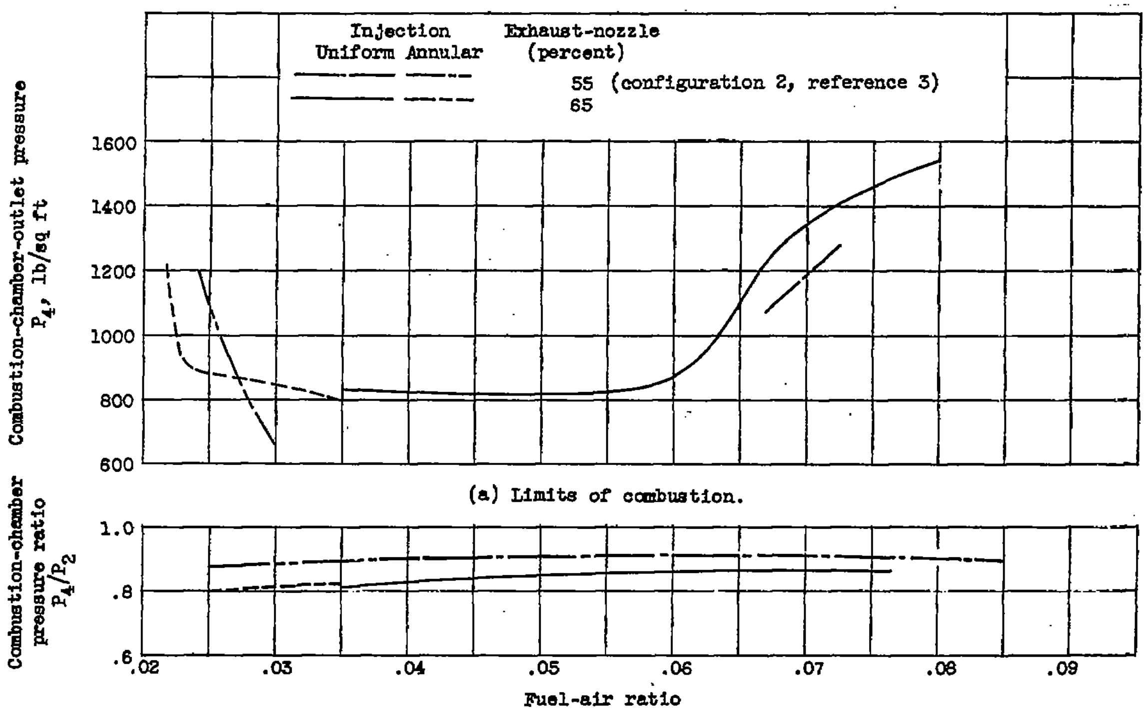


(a) Combustion-chamber-inlet Mach number.

(b) Combustion-chamber-outlet total pressure.

(c) Combustion efficiency.

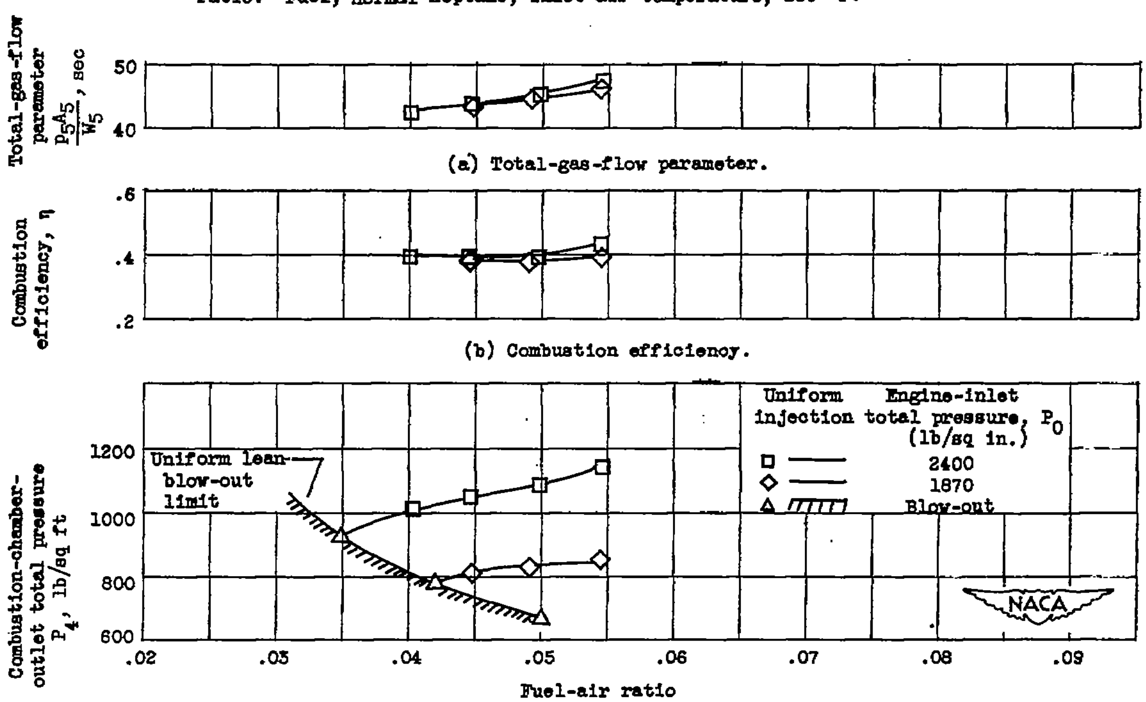
Figure 10. - Effect of exhaust-nozzle size on combustion variables. Fuel, normal heptane; altitude, 45,000 feet; inlet-air temperature, 250° F.



(a) Limits of combustion.

(b) Combustion-chamber pressure ratio.

Figure 11. - Effect of exhaust-nozzle size on limits of combustion and combustion-chamber pressure ratio. Fuel, normal heptane; inlet-air temperature, 250° F.

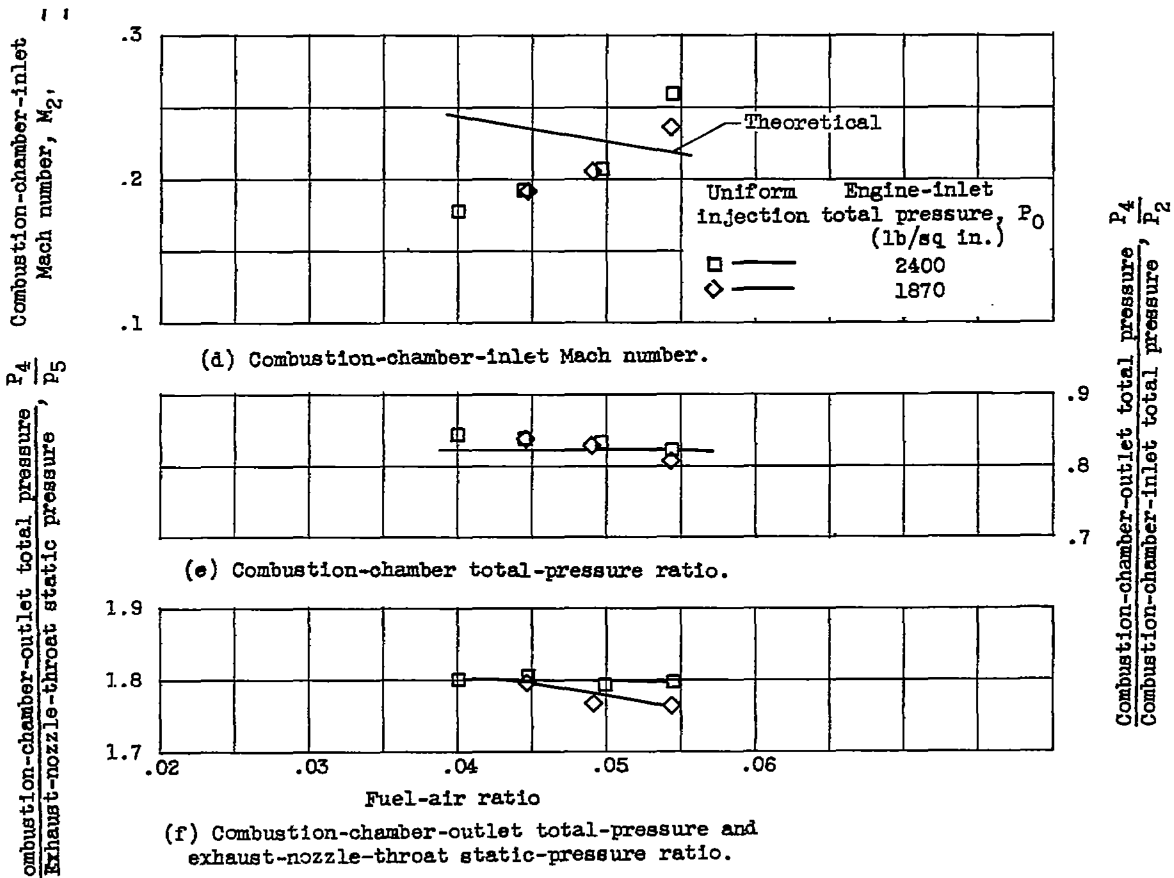


(a) Total-gas-flow parameter.

(b) Combustion efficiency.

(c) Combustion-chamber-outlet total pressure.

Figure 12. - Combustion results for 250° F inlet air. Fuel, high-speed Diesel oil.



(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Combustion-chamber-outlet total-pressure and exhaust-nozzle-throat static-pressure ratio.

Figure 12. - Concluded. Combustion results for 250° F inlet air. Fuel, high-speed Diesel oil.

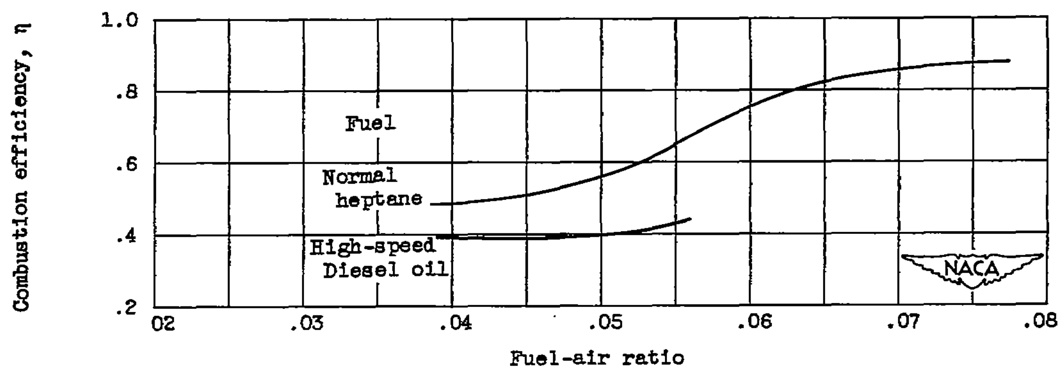


Figure 13. - Comparison of combustion efficiencies using normal heptane and high-speed Diesel fuels with 65-percent exhaust nozzle and uniform injection. Altitude, 45,000 feet; inlet-air temperature, 250° F.

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